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6. AUTHOR(S)

Conference Committee

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Politecnico di Milano
Piazza Leonardo Da Vinci 32
Milan 20133
Italy

8. PERFORMING ORGANIZATION REPORT NUMBER

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13. ABSTRACT (Maximum 200 words)

The Final Proceedings for Int'l Workshop on Errors and Noise in Energ. Material Combustion Exper., 14 March 1999 - 18 March 1999

This is an interdisciplinary conference. Topics include: Measurement techniques of thermophysical and ballistic properties of energetic materials (in particular, solid rocket propellant explosives); how to handle data especially in the presence of sensible errors and noise; and to which extent the obtained data depend on the specific data reduction technique implemented.

14. SUBJECT TERMS

EOARD, Combustion, Rocket Engines, Solid Fuels

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POLITECNICO di MILANO
DIPARTIMENTO di ENERGETICA

International Workshop on
Errors and Noise in Energetic Material Combustion Experiments

Politecnico di Milano, Milano, MI, Italy
15-16 March 1999

Second Announcement - 19 February 1999

Scope
An international workshop on "Errors and Noise in Energetic Material Combustion Experiments" will be held at Politecnico di Milano on 15-16 March 99 with optional seminar, discussion, and laboratory sessions 17-19 March 99.

The objectives of this workshop are to discuss error and noise problems arising in experiments to measure energetic material properties, and to discuss methods by which those problems can be avoided, minimized, or used to extend understanding of the material properties and behavior.

Previous workshops in this series (Combustion Instability in 1997 and Property Measurements in 1998) have highlighted the extreme importance of wider and more accurate experimental knowledge of the fundamental thermophysical and ballistic properties of energetic materials such as solid rocket propellants. The 1998 workshop, in particular, showed that even the simplest measurements are significantly affected by a variety of errors and noise of electrical, acoustic, structural, and phenomenological origins.

Presentations are sought that document the origins, treatment, and utilization of the error and noise problems encountered in laboratory, motor, or field application environments. Although emphasis will be given to steady measurements and their dependence on the operating environment, nonsteady measurements are also sought because they are more susceptible to error and noise problems.

Topics of particular interest include:

- Thermophysical and ballistic properties of energetic materials;
- Identification or demonstration of new phenomena associated with the combustion of energetic materials;
- New or improved experimental, diagnostic measurements, or data analysis techniques;
- Data analysis procedures to extract results obscured by sensible errors and background noise;
- Comparisons of results obtained by different specific data handling and analysis techniques; and
- Comparisons of results obtained from experiments using different diagnostic measurements.

Rocket and gun propellant experts, sharing the same basic problems of experimental error in thermophysics, safety, and ageing measurements, are invited to participate.

Workshop presentations are planned for two days, 15-16 March 1999. Specialized seminars and working group activities are planned for the period 17-19 March 1999. Lab facilities are available to conduct simple experiments that can be made to examine points brought out in these discussions.

Attendance
Participation by invitation only. A number of qualified researchers from several countries are expected to attend.

Speakers
Each speaker is required to provide a *one page abstract of the presentation* (including title, authors, affiliation) for distribution to all workshop participants.

In addition, each speaker is invited to provide a *copy of the transparencies used for presentation* in advance (at most at the registration time on Monday morning 15 March 99).

The maximum time allowed for presentation is 45 minutes, including at least 20 minutes for questions.

Registration
No fee requested; lunch and coffee breaks courtesy of the sponsors. Pre-Registration by e-mail is recommended (email addresses below); on-site registration will be available Monday 15 March 1999 from 9:00 to 10:00.

Sponsors
We wish to thank the following for their contribution to the success of this conference:

- Politecnico di Milano (PoliMi, Milano, Italy);
- Ministero dell'Università e della Ricerca Scientifica e Tecnologica (MURST, Roma, Italy);
- Agenzia Spaziale Italiana (ASI, Roma, Italy);
- Landau Network Centro Volta (LNCV, Como, Italy);
- European Office of Aerospace Research and Development, Air Force Office of Scientific Research, United States Air Force Research Laboratory;
- United States Army Research Development and Standardization Group (UK), and
- United States Office of Naval Research, Europe.

Approximate Exchange Rate
The exchange rate is about US$ 1 = 1,700 Lit, but is subject to fluctuations.

Lodging
Arrangements have been made for a block of rooms at the special price of Lit 125,000 (about $74) for singles and Lit 180,000 ($106) for doubles, breakfast buffet included, at the nearby

Hotel Gamma (*** category)
85 Via Valvassori Peroni, 20133 Milano, MI, Italy
e-mail: htlgamma@tin.it
Ph.: (0039-02) 2641-3152 (eight digits) NB: 0 is needed for the area code
Fax: (0039-02) 264-0255 (seven digits) NB: 0 is needed for the area code

Reservations have to be made by Workshop attendees directly with Hotel Gamma by 1 March 99, preferably by fax or e-mail. Reservations received after this date might not be accepted. Please specify the date (and expected time) of arrival and departure, and make sure to mention "Workshop DeLuca" in your reservation to qualify for the above special price.

Travel

ARRIVAL. Attendees flying from USA, Russia, and Japan will arrive to Malpensa airport (northwest of Milan), attendees flying from most European countries will arrive to Linate Airport (southeast of Milan). Attendees traveling by train from Europe will very likely arrive at "Stazione Centrale" (Central Rail Road Station). Attendees traveling by car are invited to go directly to Hotel Gamma (East of Milan) by exiting "tangenziale est" (eastern belt highway) at Lambrate or Rubattino or Linate.

Shuttle buses (just a regular size bus, clearly marked Malpensa Shuttle or Linate Shuttle) are available from both airports for several destinations. Stazione Centrale is the recommended *direction* from both arrival airports. A small section of Stazione Centrale serves also as Air Terminal and provides subway connections to all directions.

FROM MALPENSA AIRPORT. The Malpensa shuttle bus leaves every 30 minutes for Stazione Centrale. The ticket has to be bought before entering the bus, at the current cost of Lit 13,000 (less than $ 8). Signs show the way. The ride takes 50 minutes (under normal traffic conditions). There might be an intermediate stop, but the crowd will get out at Stazione Centrale.

From Stazione Centrale, a taxi to Hotel Gamma is the best option; the cost should be less than $ 20. For more daring people, a subway ride on Line 2 (the "green" line) is a cheaper alternative: the exit is (only four stops from Stazione Centrale) and the ticket costs less than 1 $.

FROM LINATE AIRPORT. Also attendees arriving to Linate airport are advised to use the shuttle bus toward Stazione Centrale, but please remember to get out at Stazione Lambrate (the first and only intermediate stop before the final stop at Stazione Centrale). The Linate shuttle bus leaves every 20 minutes for Stazione Centrale. The ticket can be bought directly from the driver on the bus, at the current cost of Lit 4,500 (less than $ 3). Signs show the way. Anyway, after exiting the custom area, get out into the traffic area and parking lots (no other option is available). You will see many taxis and buses at most 100 m far from you (depending on the exit door). The bus is clearly marked; look also for the sign STAM (Societa' Trasporti Aeroporti Milanesi) and direction "Stazione Centrale". The ride takes 15 minutes (under normal traffic conditions). The Lambrate stop is less than 100 m far from Hotel Gamma. A more expensive option is a taxi ride directly from Linate to Hotel Gamma; the cost should be around $ 20.

Should you forget to get out at Stazione Lambrate, you will necessarily reach Stazione Centrale. From Stazione Centrale, a taxi to Hotel Gamma is the best option; the cost should be less than $ 20. For more daring people, a subway ride on Line 2 (the "green" line) is a cheaper alternative: the exit is (only four stops from Stazione Centrale) and the ticket costs less than 1 $.

FROM STAZIONE CENTRALE. From Stazione Centrale, a taxi to Hotel Gamma is the best option; the cost should be less than $ 20. For more daring people, a subway ride on Line 2 (the "green" line) is a cheaper alternative: the exit is (only four stops from Stazione Centrale) and the ticket costs less than 1 $.

Local Transportation

The subway is the quickest way to move around once in town. The subway sign is a relatively big (say, 50x50 cm), well visible red sign which reads "M" or "MM" (Metropolitana Milanese). There are 3 lines (No. 1 or Red, No. 2 or Green, No. 3 or Yellow respectively from the color of the internal signs).

Please avoid private people offering a car ride, use only licensed taxis (yellow or white cars, with the sign TAXI well visible). This is particularly true at Stazione Centrale and Linate. Also, be aware of the fact that luggages require an extra fee (Lit 500 /piece) not included in the price indicated by the taximeter; similarly, all rides from Linate airport (around Lit 5000) and late evening or Sunday rides (around Lit 2000) require an extra fee. All charges are clearly indicated in several languages inside all licensed taxis.

Useful Internet Information

- For Malpensa airport, please consult the site:
http://travel.epicurious.com/travel/c_planning/06_airports/eur/milanmpa.html

- For Linate airport, please consult:
http://travel.epicurious.com/travel/c_planning/06_airports/eur/milanlte.html

- For general information about "How to reach Politecnico di Milano" (only in italian) please consult:
http://www.polimi.it/storia/sedi/comerag.html

- For maps of the subway lines, please consult:
http://www.polimi.it/storia/sedi/comerag.html

- For detailed maps of Milano, please consult:
http://www.polimi.it/storia/sedi/comerag.html

- Specific maps of the zone between Central Railway Station and "Citta' Studi" (where Politecnico is located) are available at the site:
http://www.polimi.it/cgi-bin/htimage/IMG/gen2.conf?561,293 .

- For information about the weather in Italy, please consult the site:
http://travel.epicurious.com/travel/c_planning/99_weather/intro.htm

Climate

Expected day temperature in the range 10 - 15 °C.

Miscellaneous

- ✓ Language: working language is English, no simultaneous translation will be provided.
- ✓ Service & tip: at restaurants, hotels, taxis, etc. service cost is always included, tipping is occasionally given for specially well rendered services.
- ✓ Electricity: 220 V with European type sockets.
- ✓ Credit cards: many shops and most hotels accept major international credit cards.

Social Dinner

In a typical Italian restaurant on Tuesday 16 March 99 at 21:00. Fixed price: 60,000 Lit (about 35 $) per person.

Emergency
For any urgent matter, please:

- contact the Organizing Committee at the registration desk
- for voice messages call: + (0039-02) 2399-3871, 2399-3872, 2399-3877, 2399-3912
- for fax messages dial: + (0039-02) 2399-3940
- for e-mail messages use: Menalli@clausius.energ.polimi.it
  or: DeLuca@icil64.cilea.it

For any further information, please contact:

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ERRORS AND NOISE IN ENERGETIC MATERIAL COMBUSTION EXPERIMENTS

Monday, 15 March 1999 — Politecnico di Milano, Dipartimento di Energetica

08:50 *Registration*
09:15 **Welcome Address**
G. Giambelli, Director
Dipartimento di Energetica, Politecnico di Milano, Italy
09:25 **Introductory Remarks**
L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

FUNDAMENTALS — **B.N. KONDRIKOV chairman**

09:30 **Effect of Experimental Data Accuracy on the Prediction of the Stability Condition in Solid-Propellant Rocket Motors**
B.V. Novozhilov
Institute of Chemical Physics, Academy of Sciences, Moscow, Russia
10:15 **Systematic Errors in Intrusive Concentration and Temperature Measurements in Combustion Chambers**
R. Pein
DLR German Aerospace Center, Hardthausen, Germany

11:00 *coffee break*

11:30 **Recoil Force Measurement as a Source of Combustion Mechanism Information**
V.E. Zarko, A.B. Kiskin, V.N. Simonenko, and D.V. Vdovin
Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia
12:15 **Ultrasound Measurement Method: Errors, Noise, and Sensitivity**
F. Cauty
ONERA, Palaiseau Cedex, France

13:00 *lunch*

BURNING RATE — **R. Pein chairman**

14:15 **Burning Wave Parameters, Their Pressure and Temperature Sensitivities and Burning Rate Response Functions of Solid Propellants and Monopropellants: Values and Errors**
A. Zenin and S. Finjakov
Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia
15:00 **Industrial Problems in Burning Rate Measurements**
E. Corsetti
Fiat Avio – Comprensorio BPD, Colleferro, Roma, Italy

15:30 *Coffee break*

16:00 **Error Analysis of Burning Rate Measurement Procedure**
R.O. Hessler and R.L. Glick
Consultant, Somerville, AL, USA and Consultant, Rensselaer, IN, USA
16:45 **Laboratory and Small Scale Motor Burning Rate Measurements**
M. Servieri and L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

17:30 End of session

Tuesday, 16 March 1999 Politecnico di Milano, Dipartimento di Energetica

08:55 **Introductory Remarks**
L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

BURNING EXPERIMENTS **B.V. NOVOZHILOV chairman**

09:00 **Energetic Material Combustion Experiments on Propellant Formulations Containing Prilled ADN**
A.L. Ramaswamy
University of Maryland, Maryland, USA

09:45 **Burning and Ignition Peculiarities of the Systems on the Base of AN, HAN and ADN**
B.N. Kondrikov, V.Yu. Egorshev, V.E. Annikov, and L. De Luca
Mendeleev University of Chemical Technology, Moscow, Russia

10:30 **Peculiarities of Using Microwave Technique in Solid Combustion Studies**
V.E. Zarko, D.V. Vdovin, and V.V. Perov
Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

11:15 coffee break

11:45 **Ignition of Energetic Materials at Fast Compression of Gas Inclusion. Scatter of Measurements and Unification of Results**
B.N. Kondrikov
Mendeleev University of Chemical Technology, Moscow, Russia

12:30 **About Combustion phenomena of Double-Base Propellant Under Conventional- and Plasma-Ignition Conditions**
B. Baschung and D. Grune
French-German Research Institute Saint-Louis, Saint- Louis, France

13:15 lunch

SESSION 04 **R.L. GLICK chairman**

14:15 **Filtering Techniques for Combustion Test Data Analyses**
R.O. Hessler
Consultant, Somerville, AL, USA

15:00 **Errors and Noise in Laser Recoil Measaurements**
F. Cozzi, A. Balasini, and R.O. Hessler
Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

15:45 Coffee break

16:15 **Sampling and Characterization of Condensed Combustion Products of Metalized Propellants. Problems and Perspectives**
O.G. Glotov, V.E. Zarko, V.V. Karasev, and A.D. Rychkov
Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

16:45 **Numerical Modeling of Composite Propellant Combustion**
F. Miccio
Istituto di Ricerche sulla Combustione - C.N.R., Napoli, Italy

17.15 Concluding Remarks
17:30 Closure of workshop

20.30 Farewell Dinner

Wednesday, 17 March - Thursday, 18 March – Friday, 19 March 1999

Politecnico di Milano, Dipartimento di Energetica
Laboratorio di Termofisica

Specialized Seminarars and Working Group Activities

Lab facilities are available to conduct simple experiments that can be made to examine points brought out in these discussions.

08:55 **Introductory Remarks**
L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

ACOUSTIC DIAGNOSTICS IN COMBUSTION **L. De Luca chairman**

09:00 **Underwater Burning Rate Measurements by Microphones - 1**
S. Rampichini, D. Ruspa, and L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

10:30 coffee break

11.00 **Underwater Burning Rate Measurements by Microphones - 2**
S. Rampichini, D. Ruspa, and L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

12:30 lunch

14:00 **Energetic Material Testing by Ultrasounds - 1**
F. Cauty
ONERA, Palaiseau Cedex, France and Dipartimento di Energetica, Politecnico di Milano, Italy

15:30 Coffee break

16:00 **Energetic Material Testing by Ultrasounds - 2**
F. Cauty
ONERA, Palaiseau Cedex, France and Dipartimento di Energetica, Politecnico di Milano, Italy

17:30 End of Session

Thursday, 18 March 1999 — Politecnico di Milano, Laboratorio di Termofisica

08:55 **Introductory Remarks**
L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

BURNING EXPERIMENTS — **L. De Luca chairman**

09:00 **Radiative Heat Feedback Measurements by Microcalorimeter - 1**
G. Tussiwand and M. Milazzo
Dipartimento di Energetica, Politecnico di Milano, Italy

10:30 coffee break

11.00 **Radiative Heat Feedback Measurements by Microcalorimeter - 2**
G. Tussiwand and M. Milazzo
Dipartimento di Energetica, Politecnico di Milano, Italy

12:30 lunch

14:00 **Energetic Material Testing by Ultrasounds - 3**
F. Cauty and L. Galfetti
ONERA, Palaiseau Cedex, France and Dipartimento di Energetica. Politecnico di Milano, Italy

15:30 Coffee break

16:00 **Energetic Material Testing by Ultrasounds - 4**
F. Cauty and L. Galfetti
ONERA, Palaiseau Cedex, France and Dipartimento di Energetica, Politecnico di Milano, Italy

17:30 End of Session

Friday, 19 March 1999 | Politecnico di Milano. Laboratorio di Termofisica

08:55 **Introductory Remarks**
L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Italy

LASER SUSTAINED COMBUSTION **L. De Luca chairman**

09:00 **Laser Recoil Experiments - 1**
F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler
Dipartimento di Energetica, Politecnico di Milano. Italy and Somerville, AL, USA

10:30 coffee break

11.00 **Laser Recoil Experiments - 2**
F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler
Dipartimento di Energetica, Politecnico di Milano. Italy and Somerville, AL, USA

12:30 lunch

14:00 **Laser Recoil Experiments - 3**
F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler
Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

15:30 Coffee break

16:00 **Laser Recoil Experiments - 4**
F. Cozzi, L. Asa, S. Palozzo, and R.O. Hessler
Dipartimento di Energetica, Politecnico di Milano, Italy and Somerville, AL, USA

17:30 End of Session

ERRORS AND NOISE IN ENERGETIC MATERIAL COMBUSTION EXPERIMENTS

ABSTRACTS

BURNING EXPERIMENTS

Radiative Heat Feedback Measurements by Microcalorimeter
G. Tussiwand and M. Milazzo
Dipartimento di Energetica, Politecnico di Milano. Italy

Underwater Burning Rate Measurements by Microphones
S. Rampichini, D. Ruspa, and L. DeLuca
Dipartimento di Energetica, Politecnico di Milano. Italy

Radiative Heat Feedback Measurements by Microcalorimeters

G.S. Tussiwand and M. Milazzo
Dipartimento di Energetica, Politecnico di Milano, Milan, Italy

Changes in the steady burning rates of solid rocket propellants caused by radiant heating have been investigated since the 60's both in the US and former Soviet Union. As a matter of fact, radiant heat is responsible for increased burning rates of both small and full scale motors with respect to strand burner values. Therefore, for motor applications burning rate data obtained from strand burners need to be corrected by a scale factor. Several efforts have been made to propose theoretical models (e.g.: Summerfield, Ibiricu and Williams, Brewster and Son) and/or develop diagnostic techniques to measure the natural thermal radiation emitted by the flame of burning propellant samples (e.g.: Zenin, Beyer). At Laboratorio di Termofisica (LTF), combustion of propellant strands under a laser beam has already been tested. We are now trying to measure the natural radiant flux emitted by burning propellant sample for nonaluminized and aluminized AP-HTPB propellants. The radiant flux will be measured using a thin copper disk as sensing element, following a technique first used by Zenin. Measurements, however, are affected by convective and radiative heat losses. Simulations with a first order concentrated parameter model show that convective losses occur even at very low radiant fluxes (such as 0.1 W/cm^2), while radiative losses become important at higher heat fluxes. Thus, a calibration procedure taking into account convective losses seems necessary to improve the quality of measurements and increase the sensibility of the calorimeter. Attempts to limit the errors produced by the unavoidable, nonlinear radiative losses, particularly important when burning aluminized propellant samples, are discussed.

Underwater Burning Rate Measurements by Microphones

S. Rampichini, D. Ruspa and L. De Luca
Dipartimento di Energetica, Politecnico di Milano, Milano, Italy

Samples of ammonium perchlorate (AP) - based composite solid propellant are ignited and burned in a chamber filled with water and pressurized by a gas (air or nitrogen). The acoustic signal of the combustion precess is picked up by two microphones: one submerged in water and the other located in the pressurized gas volume. This signal is first analyzed in the time domain to obtain preliminary information about the mean (quasi-steady) burning rate. The different components of the signal are then resolved in their frequencies using a FFT. Since frequencies are observed to change in time these are conveniently studied through a Spectrogram (or Sonagram) technique. Notches cut on the propellant strand are usually revealed by the spectrogram. In principle, this allows to deduce more accurate quasi-steady burning rate measurements than those obtained in standard acoustic burners. Transient combustion phenomena as well, including effects due to propellant heterogeneity, appear to be revealed by the collected spectrograms. In particular, extinction phenomena and ignition delays are discussed.

ERRORS AND NOISE IN ENERGETIC MATERIAL COMBUSTION EXPERIMENTS

ABSTRACTS

Monday, 15 March 1999

FUNDAMENTALS

Effect of Experimental Data Accuracy on the Prediction of the Stability Condition in Solid-Propellant Rocket Motors
B.V. Novozhilov
Institute of Chemical Physics, Academy of Sciences. Moscow. Russia

Systematic Errors in Intrusive Concentration and Temperature Measurements in Combustion Chambers
R. Pein
DLR German Aerospace Center, Hardthausen, Germany

Recoil Force Measurement as a Source of Combustion Mechanism Information
V.E. Zarko, A.B. Kiskin, V.N. Simonenko, and D.V. Vdovin
Institute of Chemical Kinetics and Combustion, Russian Academy of Sciences, Novosibirsk, Russia

Ultrasound Measurement Method: Errors, Noise, and Sensitivity
F. Cauty
ONERA, Palaiseau Cedex, France

BURNING RATE

Burning Wave Parameters, Their Pressure and Temperature Sensitivities and Burning Rate Response Functions of Solid Propellants and Monopropellants: Values and Errors
A. Zenin and S. Finjakov
Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia

Industrial Problems in Burning Rate Measurements
E. Corsetti
Fiat Avio – Comprensorio BPD. Colleferro. Roma. Italy

Error Analysis of Burning Rate Measurement Procedure
R.O. Hessler and R.L. Glick
Consultant, Somerville, AL, USA and Consultant, Rensselaer, IN, USA

Laboratory and Small Scale Motor Burning Rate Measurements
M. Servieri and L. DeLuca
Dipartimento di Energetica, Politecnico di Milano, Italy

Effect of Experimental Data Accuracy on the Prediction of the Stability Condition in Solid-Propellant Rocket Motors

B.V. Novozhilov
Institute of Chemical Physics, Russian Academy of Sciences, Moscow, Russia

To predict the stability condition of a steady-state combustion regime in a solid-propellant rocket motor one should know so called propellant response function to oscillatory pressure. There are two ways to obtain these functions: firstly, from a direct experiment, for example, in T-burner, and, secondly, by the help of a theory. In this report, only the second way is discussed. Because any theory involves into

consideration some experimental data, the influence of experimental data errors is discussed on the accuracy of the response functions obtained theoretically.

Consideration is presented in the framework of the Zel'dovich-Novozhilov theory. The explicit expression of the propellant burning rate, burning temperature, and gas velocity response functions to oscillatory pressure are investigated to reveal the general properties of the solid propellant response functions:

a. They have a great sensitivity to propellant parameters at frequencies close to the natural frequency.

b. There is also a great sensitivity to small changing propellant model.

The accuracy of the stability condition of a steady-state combustion regime in a solid-propellant rocket motor is estimated taking into account also the motor nozzle response function to oscillatory pressure.

The result of the presented consideration may be formulated in the following form. The theoretical values of both the response functions and the stability condition might be obtained with reasonable errors provided that steady-state experiments have rather high accuracy.

Systematic Errors in Intrusive Concentration and Temperature Measurements in Combustion Chambers

R. Pein
DLR - German Aerospace Center, 74239 Hardthausen, Germany

Measurements of species, temperature and velocity distribution in combustion chambers are of great importance in aerospace applications. The exact knowledge of these data is necessary for determination of reaction zones, mixing and combustion efficiencies as well as pollutants in propulsion systems like rockets and ramjets. The results should lead to a better understanding of the combustion process, to an improved design of the propulsion system under investigation, and to a validation of existing computer codes. This should also reduce the necessary number of test runs in test facilities and finally decrease the costs of such operations.
The typical systematic errors which are made during intrusive concentration and temperature measurements in combustion chambers are illustrated. Besides isokinetic and representative sampling the most important factor is the rapid quench of the combustion gases and freezing of the composition of the combustion products. This is studied in detail by means of a simple analytic heat transfer model for the sampling probe. Plug flow and constant mean properties of the gas is assumed as well as constant wall temperature of the probe. The results are expressed in terms of temperature-time histories, temperature profiles and quench rates inside the probe. The dependence on probe diameter, probe mass flow rate, initial temperature and probe wall temperature is discussed. It is shown that only for probes with very small diameters and for low mass flow rates very high initial quench rates up to 10^{10} K/sec can be achieved. The quench process then is completed after a few centimeters probe length. Most sampling probes are too large in diameter. A comparison with chemical reaction rates and literature data shows that it is impossible to quench radical reactions, and, for lower quench rates the measurement errors of minor species like CO and NO are larger than for the main species. Thus this measurement method is limited to not too high combustion temperatures. It is also shown that the temperature of the probe wall has negligible effect on the quench rate. This is of interest for experiments where it is necessary to avoid condensation in the probe by heating the cooling water.
Another important item is the formulation of a mole balance in terms of atom conservation equations in order to validate the results of concentration measurements. Each experimental result should be checked for fulfilling the mole balance. If this is not the case the value should be discarded. A mole balance can also be used for calculating the concentration of a missing component.
The main errors of high-temperature thermocouple measurements, especially the radiation correction are also discussed in detail. A small heat transfer model for the calculation of the radiation correction is evaluated. The results show that the most important parameter is the bead size. For minimization of the radiation losses the bead size should be as small as possible. Another parameter causing some uncertainty is the emissivity of the thermocouple material which is dependent from temperature and composition of the bead. For exact measurements it is also necessary to know at least approximately the chemical composition of the environment in which the temperature measurement is done. Measurement errors can also result from resulting from catalytic effects and high temperature oxidation of thermocouple material.

Recoil Force Measurement as a Source of Combustion Mechanism Information.

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Principles of measurement of recoil force with capacitance and inductive based gages are discussed. Theoretical background of the measurement method is presented. Possible sources of errors in obtaining and treatment of experimental results are analyzed. The errors may appear due to variation of environmental conditions as well as disturbances of combustion because of bad ignition and interaction with inhibiting layer, and due to vibration and electrical noise. Examples of the recoil force records in combustion of different types of solid propellants are presented and discussed. Potentialities of combined measurement of recoil force and dynamic mass loss for deriving new information about combustion mechanism are discussed.

Ultrasound Measurement Method: Errors, Noise, and Sensitivity

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The ultrasound measurement method has been widely applied to determine the burning rate of solid propellants. This contribution is aiming at discussing about the reliability, the accuracy of the method and, finally, of the burning rate evolution deduced from the propagation time variation.

There are, at least, three points of interest.

- the scale factor: the burning rate has to be defined from a tiny sample to a full-scale rocket-motor. It takes place in the framework of the RTO WG27,
- the accuracy of the method including propagation through the condensed phase and the effect of the operating conditions,
- the computation errors related to the derivative function determination and the corrective terms taken into account in the measurement theoretical approach.

What is considered as errors or noise on the measurement as well for the ultrasound echoes evolution as for the burning rate scattered results could be source of information. Examples illustrate the presentation.

Burning Wave Parameters, Their Pressure and Temperature Sensitivities and Burning Rate Response Functions of Solid Propellants and Monopropellants: Values and Errors

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The paper presents results of experimental measurements of burning rates and burning surface temperatures at various pressures and initial sample temperatures of solid monopropellants and propellants. Errors of the measurements are discussed.
Pressure and temperature sensitivities of these parameters are determined on the base of the measurements. Errors of the determinations are estimated.
Burning rate response functions to acoustic pulsations are calculated on the base of the obtained sensitivities. Errors of the calculations are estimated.
Conclusions are made about peculiarities of the obtained sensitivities and burning rate response functions.

INDUSTRIAL PROBLEMS IN BURNING RATE MEASUREMENT

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Aim of this presentation is to describe the state of art of the burning rate measurement technique performed in industry, and in particular at FIAT AVIO BPD, pointing out the problems arising and discussing some possible solutions which can avoid or minimize them.

As solid propellant burning rate is an essential parameter for the design of solid rocket motors, an error in burning rate evaluation leads to an even worst error in motor performance prediction. So, it is evident how important very accurate burning rate measurement is, even if, for industrial application, the main goal is to achieve the highest reproducibility of it. In fact, repetitive correlation between sub-scale and full-scale motors on burning rate (i.e. scale factor) allows to make motor performance prediction with a higher confidence level.

Three types of industrial sub-scale motors are actually in use at FIAT AVIO BPD for solid propellant burning rate measurement: Crawford bomb, 2 and 6 inch bombs, BARIA bomb (used only in Ariane5 program). Their main measure problems have been taken into account, highlighting the possible causes of dispersions and errors, due both to hardware (i.e. data acquisition system, grain defects, bomb design, etc.) and software (i.e. data reduction method). Corrective actions and proposed improvements are also presented.

Error Analysis of Burning Rate Measurement Procedures

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and

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Burning rate measurement procedures are contrasted, using a round robin dataset of simulated motor data having either instantaneous or non-instantaneous burnout as the principal variable. Bias error components of two historical procedures are specifically identified and measured. An iterative least-squares group analysis is shown to improve results from the historical procedures by eliminating the effect of non-neutral pressure-time histories. A two-point measurement procedure is shown to produce bias-free results for these simulations.

Laboratory and Small Scale Motor Burning Rate Measurements

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The purpose of this paper is to describe the influence of noise in measuring steady burning rates in strand burners and small scale motors. In strand burners, two techniques to measure steady burning rates, fuse wires and video camera, are presented and compared to highlight affinities and differences; the comparison shows that the video technique gives better results. In both cases, it will be pointed out what kind of errors are usually done and how much they affect the final results. In small scale motors, using the "thickness over time method" to measure steady burning rates, web thickness is taken as the nominal one while time interval is detected from the pressure profile. Errors depend on time resolution, and especially on noise polluting pressure profiles. A possible solution to solve this problem is the moving average. An application to real motors is discussed.

Tuesday, 16 March 1999

BURNING EXPERIMENTS

Energetic Material Combustion Experiments on Propellant Formulations Containing Prilled ADN
A.L. Ramaswamy
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Burning and Ignition Peculiarities of the Systems on the Base of AN, HAN and ADN
B.N. Kondrikov, V.Yu. Egorshev, V.E. Annikov, and L. DeLuca
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Peculiarities of Using Microwave Technique in Solid Combustion Studies
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Ignition of Energetic Materials at Fast Compression of Gas Inclusion. Scatter of Measurements and Unification of Results
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About Combustion phenomena of Double-Base Propellant Under Conventional- and Plasma-Ignition Conditions
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SESSION 04

Filtering Techniques for Combustion Test Data Analyses
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Errors and Noise in Laser Recoil Measaurements
F. Cozzi, A. Balasini, and R.O. Hessler
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Sampling and Characterization of Condensed Combustion Products of Metalized Propellants. Problems and Perspectives
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Numerical Modeling of Composite Propellant Combustion
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Energetic Material Combustion Experiments on Propellant Formulations Containing Prilled ADN

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A new formulation composition containing prilled particles of ADN as the oxidizer component was studied. The composition was formulated at NSWC with prills manufactured at Thiokol and CSD. Strand ballistic burn rate data on the propellant formulation showed that the overall performance of the formulation was sensitive to the prill microstructure. Further microstructural characterization of the formulation by ESEM (Environmental Scanning Electron Microscopy) combustion experiments showed that the performance of the composition could further be improved by tailoring the microstructural characteristics of the composition. Such parameters are not revealed by strand burning rate measurements which represent an average or overall measurement and pick up on the localized rate variations as "noise", averaging them out. Microstructural characterization (such as filming the propellant combustion at the highest magnifications and examination of quenched samples) of propellant formulations may thus provide some of the complementary data to the standard propellant characterization measurements to reduce/eliminate measurement errors. Furthermore with prilling the errors are reduced and the performance improved as will be described.

Burning and Ignition Peculiarities of the Systems on the Base of AN, HAN and ADN

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Ammonium and hydroxylammonium salts of nitrogen containing acids are the well-known bases for formulation of different kinds of energetic materials, particularly rocket and gun propellants. Ammonium nitrate, AN propellants are being known for about a century. Burning of these EM was studied extensively in many laboratories but burning characteristics and mechanism of the steady state and unstable combustion of them are stated till now only very approximately, intensive additive investigation is needed. It is especially true in correspondence to the relatively new energetic materials of this sort, HAN and ADN or to the mixtures of AN with such an energy reach metal as Magnesium that to the contrary of Aluminum is used in the propellants formulations relatively rarely.

In this work we have investigated mechanism of ignition of AN/Mg mixtures by irradiation of CO_2 laser and burning of this compound in comparison with other dry and water impregnated systems containing AN, HAN and ADN. In all cases mechanism of the basic physico-chemical transformations was supposed to be stated and the strong difference in ignition and burning characteristics between compositions containing these oxidizers was elucidated.

The main difference as to the burning characteristics, first of all burning rate and its pressure dependence, is concerned consists in the fact that HAN and ADN systems burn much faster then AN mixtures are found to burn. The great variety of constants in Vielle law is also determined. For instance HAN in the crystal form, first investigated, has pressure exponent as high as 2.5 in the pressure interval of 3 to 50 atmospheres, whereas ADN has only about 0.6, at approximately the same velocity of the combustion wave near the upper border of the interval. At about the same pressure ADN is subjected to burning instability. Correspondingly the big scatter of burning rates may be noted which is changed at still higher pressures with a region of steady combustion with moderate velocity.

At elucidation of the facts and laws this estimated the abundant experimental information concerning some of the others N-acids salts burning is successfully used.

Peculiarities of Using Microwave Technique in Solid Combustion Studies

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The principles of microwave method for measuring current length of burning propellant sample are described and different schemes of measuring unit are discussed. Theoretical limits of space resolution of devices working in 2-30 mm band are explored. The examples of typical records of 2mm band microwave interferograms in combustion of non-metallized and metallized composite propellants are presented. It is shown that there exist several sources of noise and errors when doing combustion experiments with microwave technique. Accuracy of the length measurement depends on accuracy of the wavelength determination and on disturbances of signal due to inherent roughness of the burning surface and surface curvature because of non-flat ignition. Losses of microwave energy depend on the nature of material and scattering on micro inclusions. Suggestions on proper use of microwave technique for burning rate measurements are formulated.

Ignition of Energetic Materials at Fast Compression of Gas Inclusions. Scatter of Measurements and Unification of Results

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Theory of energetic materials (EM) initiation at weak mechanical stimuli was created in the very beginning of 40th. Prof. Yuly Khariton in 1940 solved two problems concerning temperature rise at penetration of a plate into mass of a liquid and at compression of the liquid layer between two polished rigid surfaces. At the same time a young engineer Khariton M. Lavrik found the cardinal solution of a problem of in bore premature explosion of artillery shells. He suggested that initiation of explosive inside the shell was a result of fast compression of a gap at the bottom of the shell filled in by air or a mixture of air and solvent vapors. A little later Prof. Frank P. Bowden in England carried out a series of the shining, eventually classic, experiments, with explosive liquids containing small bubbles of a gas to demonstrate extremely strong influence of the bubbles on the level of sensitivity of the liquids to impact.

During half of a century to proceed after these events theory of initiation at slow mechanical stimuli had developed preeminently along the ways marked by these discoveries. A group of scientists in the Institute of Chemical Physics, Moscow (A. Dubovik, A. Denisaev, et al.) elaborated the Bowden conception. American investigators (J. Starkenberg, M. Hershkovitz, et al.) developed essentially the problem of set back. The group of Prof. F. Bowden followers (J. Field, G. Cooley, et.al.) performed the extensive investigations in the Laboratory of Surfaces. Cambridge University.

One of the peculiarities of experimental investigations in the field of initiation of explosives is the unusually strong scatter of the experimental results. Curve of frequency of explosions versus energy, pressure or velocity of impact usually intends to proceed with a very low tangent to the horizontal axis. Critical value of the influence sometimes seems to be estimated with a very low level of exactness.

To avoid this difficulty several series of experiments were performed in our Laboratory with different types of tools providing the special kind of impulsive coercion on a small sample of EM. Experiments were performed in collaboration with Yu.N. Polikarpov and. by the late, E.I. Dorofeev.

Ignition at quick compression of gas intrusions of a row of liquid EM was being investigated by means of application of the steel U-shaped tube one end of which was connected through the plastic disc with receiver containing compressed nitrogen. Another end of the tube was sealed. The explosive liquid was immersed in the lower section of the tube. When the plastic disc was ruptured the column of liquid in the tube is set to motion by the jet of nitrogen rushing into the tube and impinges upon the tube end. The procedure can be used to produce data that revealed the role of air inclusions in causing ignitions during the rapid compression of a liquid in the broad range of conditions of its production or transportation. The simple formula

$$\mathbf{P}_{cr} = \left[\left(\frac{\mathbf{x}_0 \mathbf{P}'_0}{\mathbf{u}_0 \rho \mathbf{R} \mathbf{T}_b} \right)^{\frac{\gamma-1}{\gamma(v-n)+1}} - 1 \right] (\gamma - 1)^{-1}, \quad (1)$$

(Where P_{cr} is the critical pressure (critical driving force) necessary for initiation, P_0' is the arbitrary rate of the pressure drop. x_0 is the original gap width. u_0 and v are the constants of the Vielle law. ρ is the density of the liquid. R is the specific gas constant. T_b is the adiabatic temperature of burning, γ is adiabatic exponent and n is a constant reflecting dependence of P_0' on pressure in the gap) is proposed to calculate the critical driving force resulting in initiation of the liquid.

A set of 21 liquid high explosives investigated is divided in three groups. The first of them includes very sensitive explosives (NG, Methylnitrate, NGL, FEFO, ADN melt, etc.) subjected to initiation in the range of P_{cr} of 8 to 23 atm. Explosives of moderate sensitivity (TNT melt and DNT/Nitric Acid 70/30 solution) are initiated in the range of 60 to 80 atm. At last, the liquid explosives of the third group assumed to be insensitive liquids (NM, TNM, water-impregnated explosives), can not be ignited at the limit pressure of our installation, 100-150 atm.

The formula (1) gives a good fit to the experimental results only for the liquids of the first group. The second and the third groups representatives demonstrate P_{cr} data several times higher than the formula (1) to provide. It is disclosed in this presentation that the difference is stipulated by the fact that at very high final pressure in the gap the strong compression of the liquid and expansion of the tube take place followed by the loss of energy and corresponding P_{cr} enhancement. An expression of the form

$$\Delta P_{cr} = x P_f^2, \quad (2)$$

(Where ΔP_{cr} is the difference in the driving force connected with the effects of compression and expansion, P_f is the final pressure in the gap and x is the function of compressibility of the liquid and geometry and mechanical characteristics of the tube) is proposed to explain the results of the majority of measurements.

Another procedure consists of employment of the fallhammer impact machine (up to 36 kg falling weight, 1.5 m height limit). The impact device contains a hole of the definite diameter and depth at the bottom of which the small portion of solid explosive is pressed. The plastic substance, ceresine (wax from ozocerite) flows into the hole under the falling weight impact, and compresses air inside the hole. The method reflects some of the conditions of ignition of explosive at in bore premature explosions. Six high explosives were investigated: TNT, TNT/RDX 40/60, Okfol (HMX + 3.5% phlegmatizer), Comp. 1 (RDX + 5-6% phlegmatizer), Comp. 2 (Comp.1 + 20% atomized aluminum) and Comp. 3 (RDX, TNT, Al and a phlegmatizer). In all cases the results of the experiments in log p_m (maximal pressure of impact) vs. log v_0 (initial volume of the cavity) plane have a form of a cloud of «go» and «no-go» points strictly divided from the cloud of only «no-go» points with a straight line

$$\log p_m = m - n \log v_0, \qquad (3)$$

where m and n are constants. In correspondence with a theoretical model n is close to 1/3 if a height of the hole were equal the hole diameter.

As a result the relation

$$Z = P\, V_0^n \qquad (4)$$

where $P = p_m/p_0$, $V_0 = v_0/v_{00}$ and $(p_0 \cdot v_{00})$ = Const. (0.1 MPa and 1 mm^3, corr.) was used to construct an «invariant of ignition probability» which does not depend on pressure of impact and a volume of cavity per se. This allows particularly to derive the density of ignitions probability ω as a function of Z and to calculate the maximal permissible stress at a given volume of the cavity, or the maximal permissible volume at a given maximal stress, corresponding to probability of ignitions preeminently designated.

In the case of TNT and in some other cases, at more complicated conditions of the experiment, the numbers n and m may change steeply at the v_0 enhancement. The model undergoes the definite alteration. However the critical character of the overall dependence, the sharp border between ignition and non ignition areas are preserved in all of the cases, and the method of calculation of the parameters of ignition would remain as before.

About Combustion Phenomena of Double-Base Propellant Under Conventional- and Plasma–Ignition Conditions

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As it sometimes happens at real firings, the weapon destroys by faulty propellants or by unsatisfactory ignition. This last point is well known as *negative difference gas pressure* established by calculations of the interior ballistic cycles. These effects are disastrous as well as in rocket motors. Numerous experiments are performed to predict a faultness combustion of the used solid propellant so the risk of weapon destruction can be minimized.

This report describes some closed vessel methods to check a regular burning behavior or to interpret an irregular combustion. It is shown by experimental results that this irregular combustion is noticed by the followed circumstances:

1. Faulty manufacturing process: the propellant grains are broken in a very early phase of the combustion.
2. Incompatible components in the propellant mass: the burning becomes irregular and changes from burning to deflagration. Pressure rise and burning interruption explain this behavior.
3. Changing of the mechanical qualities: it is shown by burn rate measurements that the brittle point of JA2 is reached near –40°C.
4. Incorrect ignition: as an example, results of a new ignition system (ETC) show the influence of the propellant position in the propellant bed on the combustion.

Micro-porosity by thermal defects is not considered here. But a new method is proposed to define a critical porosity of the propellant.

Noise and Errors in Laser Recoil Measurements

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Laser recoil is a diagnostic technique, originally proposed in the United States (1972), to assess the combustion response of solid rocket propellants. This technique evaluates the response of the tested material to fluctuations of radiant heat flux by directly measuring the recoil force generated by the mass efflux from the burning surface. A CO_2 or Nd:YAG laser is the radiant source commonly used today. This approach allows several advantages with respect to standard techniques: measurement of the combustion response can be direct, both magnitude and phase can be measured, in principle no frequency limitation exists, many frequencies can be tested in just one experimental run, operations are fast and cheap, small size samples are needed. Thus, laser recoil is a promising technique. Nevertheless difficulties are also met. In particular, the small value of recoil thrust oscillations (few hundredth of grams) requires a very sensitive force transducer and great care in minimizing noise and errors sources. Acoustic pressure waves, mechanical vibrations, electric interferences, and background noise are able to deteriorate the quality of the measured signals, thus increasing data scatter and making interpretations of final results difficult. This is especially true for those materials showing a low response to heat flux, such as HMX, RDX and AP-based solid propellants when tested under a CO_2 laser. A comparison of measured CO_2 laser-driven combustion response for three different solid propellants is reported and noise effects are discussed. Some hints to reduce noise and errors are suggested, and results so far obtained are shown.

Sampling and Characterization of Condensed Combustion Products of Metalized Propellants. Problems and Perspectives

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Problems of representative sampling and subsequent characterization of the condensed combustion products are shown to connect closely with mechanism of formation of metal agglomerates, their structure and motion in two-phase flow, temporal evolution of size distribution, etc. Important feature of combustion process is its statistic and stochastic character that leads to formation of polydisperse size distribution of agglomerates with different internal structure. These issues should be taken into account in analysis and comparison of available experimental data. For illustration, experimental data are presented corresponding different propellant types.

To get reliable information about the combustion law of real agglomerates and to solve specific problems of data analysis and interpretation a novel experimental approach is discussed. The approach provides obtaining given size agglomerates burning in well characterized conditions. For this end special "super heterogeneous propellant" is designed and tested. The propellant consists of homogenized non-metalized matrix, which contains finite number of small volume inclusions of highly metalized energetic material simulated the content of "pockets" in real composite metalized propellants. In combustion of super heterogeneous propellant each inclusion generates agglomerate that burns in the flow of combustion products of non-metalized matrix.

Some calculation results are presented of two-dimensional two phase flow in actually used sampling bomb geometry along with first results of experimental study of burning and drag law for model agglomerates formed in combustion of super heterogeneous propellant.

Numerical Modelling of Composite Propellant Combustion

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An innovative 2D numerical model of composite propellant combustion is proposed. It takes into account the detailed description of the propellant topology, five chemical reactions, gas molecular diffusion and heat transfer in gas phase. Partial differential equations are numerically solved introducing a topological matrix. The propellant surface is determined by scanning the topological matrix and performing a series of logical tests. The bi-dimensional profiles of the temperature and molar fractions in the spatial domain are obtained. The average surface temperatures are also evaluated in both binder and oxidizer regions, as well as the linear burning rate. The model is able to predict the time evolution of the composite propellant after ignition. A non planar evolution of the propellant surface is predicted during combustion for different propellant topologies according with experimental observations of the propellant surface reported in literature. The propellant topology,. the pressure, the oxidizer-binder mass ratio and the characteristic dimension play a large role on surface temperatures and linear burning rate. They increase with pressure and decreases, with asymptotic tendency, at increasing of both mass ratio and characteristic size. High burning rate are predicted for topologies which enhance the mixing between binder and oxidizer, in particular when fine spherical particles of the oxidizer are dispersed within a binder matrix.

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